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Production of methanol from a mixture of torrefied biomass and coal

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ABSTRACT

This paper investigated the influence of adding torrefied biomass within an entrained flow coal gasifier for the production of methanol. Computer simulations of gasifying a mixture of torrefied biomass and coal within an entrained flow gasifier, synthesis gas purification, and methanol synthesis were carried out using the Aspen plus program package. In addition, economic analyses are presented based on the net present value. It was shown that, based on the predictions for future prices of the raw materials and methanol, usage of a mixture of biomass and coal within entrained flow gasifiers would be feasible and could become economically even better than the usage of coal only. The net emissions of CO_2 would also be significantly lowered.

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1. Introduction

Energy demands have increased substantially over the last decade [1] and consequently alternative energy sources are becoming a greater necessity [2]. Therefore researchers are focussing on the development of processes and technologies that are environmentally-friendly, whilst ensuring reasonable standards of living throughout our world [3]. Biomass is one of the more important potential sources for the production of synthetic fuels [4] and energy, especially in Slovenia being one of the more forested countries in Europe with over 50% of its area covered by forests. Furthermore, Slovenia is one of a few countries to have a positive increment of wood biomass. The annual increment is approximately 7 million cubic metres, of which about 4.9 million cubic metres are available for energy production [5]. This potential is not fully utilised presently because the properties of biomass restrict its wider uptake by industries. Furthermore, biomass is more expensive than coal but carbon-trading laws are a good motivation for greater usage of biomass [2].

A significant number of studies exist regarding techno-economic evaluations of methanol production. Methanol is usually produced from natural gas, coal, petroleum oil, etc. [6], however the future direction of methanol production technology is in replacing fossil sources with renewable energy sources and biomass has been considered within significant studies [7]. Another important approach is the integration of the methanol production process with chemical processes, refineries, the pulp and paper industry [6], and district heating systems [6,7].

The formations of tar and char during biomass gasification can be very problematic when using conventional biomass gasification systems such as the interconnected fluidised bed gasifier [8], causing pipe-blockages of the down-stream equipment. However, in order to use biomass in entrained flow gasifiers, the biomass must be pulverised to particle sizes of 100 μm, which is a necessity for these types of gasifiers [9,10] and large energy consumption is needed to pulverise raw biomass [11]. Over recent years several studies have been conducted in order to improve the properties of biomass, with one of the developed methods being considered as more promising. This is the so-called torrefaction of biomass. Torrefaction, also known as mild pyrolysis, is a process where biomass is exposed to 200–300 °C within an anaerobic environment [9,10]. During this process the water evaporates, together with certain other volatiles, and the lignocellulosic biopolymers partially decompose. This results in a loss of about 20% of the initial mass, and 10% of the initial heating value. Torrefaction technology greatly reduces the tenacity of biomass, therefore the power consumption needed for grinding torrefied biomass is reduced by 80–90% in comparison to raw biomass [11]. The grindability of torrefied biomass is comparable to that of coal; therefore it can be gasified in entrained flow gasifiers with high cold gas efficiencies [11]. The torrefaction process improves not only the energy density of the biomass but also other properties such as the ability of pelletisation, and hydrophobic nature [12]. Torrefaction also increases the homogeneity of the material and storing is also easier due to the hydrophobic properties of the torrefied biomass. It is for these reasons torrefied biomass is easily transported and can be used for

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high temperature gasification applications. The torrefied biomass could be partly or totally substituted for coal within the entrained flow gasifiers in order to obtain synthesis gas. The reason why biomass could be used is its high availability in Slovenia. Nonetheless, as biomass is considered as a renewable-energy source, it reduces the values of the carbon taxes that must be paid for fossil fuel usage. This is also the main reason why biomass is considered in this work, even though coal is cheaper.

Synthesis gas obtained from the gasifier is further used for methanol production. As the amount of hydrogen in it is insufficient, syngas firstly undergoes a WGSR (water–gas shift reaction) and is then conveyed to a methanol synthesis reactor. The needed amount of hydrogen can also be provided from water electrolysis [13] but this method is not used in this case as the WGSR is usually used for the industrial production of methanol.

The second part of this paper presents an economic analysis of the whole process, including torrefaction of biomass, gasification, and methanol production. It is for this purpose that some approximations and assumptions have been made due to the lack of information. Economic analysis is based on net present value. Predicted prices for the reactants and products have been used in order to calculate the future values of revenue. The predicted prices have been calculated using World Bank price indices, and such prices on average outperform the random walk forecasts or extrapolations of recent price trends [14].

1.1. Torrefaction of biomass

The process of biomass torrefaction is a promising process for increasing the amount of biomass used for gasification processes. As stated previously, raw biomass cannot be used within a high temperature coal gasifier but, on the other hand, torrefied biomass can.

The process of torrefaction consists of five stages. During the first stage biomass (usually wood) is initially heated, then drying occurs, and at the end of this stage the moisture starts to evaporate. Free water evaporates at a constant rate during the second stage. A constant rate of evaporation also means a constant temperature. During this stage the biomass loses from 5 to 10% of its initial mass, and after that point is reached, the rate of the evaporation decreases, indicating the end of the second phase. An additional amount of physically-bonded water is released during the third stage whilst the biomass is being heated to 200 °C. Some lighter organic compounds could also evaporate during the third stage, which is finished when the temperature exceeds 200 °C. At that point the fourth stage starts, which lasts until the temperature is decreased to 200 °C. The actual process of torrefaction occurs during this stage. The final (peak) temperature varies between 200 and 300 °C, and the residence time from 60 to 90 min. This stage consists of both heating and cooling periods. Devolatilisation begins during the heating period. The process of mass loss is continued during the period of constant temperature until the cooling period. The final stage of biomass torrefaction is further cooling from 200 °C [12].

The necessary heat for torrefaction and pre-drying is produced by the combustion of the liberated torrefaction gas. An auxiliary fuel could possibly be used when the energy content of the torrefaction gas is insufficient to thermally balance the torrefaction process [15].

Several choices should therefore be made as there are several ways of modelling the torrefaction process. For example, it should be decided as to whether biomass would be heated directly or indirectly. The process modelling and simulation of biomass torrefaction is outside the scope of this paper. The properties of the torrefied biomass that are needed for further simulations are given in Ref. [16].

1.1.1. Properties of torrefied biomass

The process of biomass torrefaction improves the properties of biomass, and consecutively increases its price. The properties of the torrefied biomass are similar to the coal properties. Even though coal has a lower price, and a slightly higher energy density, the torrefied biomass can produce a better way in practice. The main advantage of torrefied biomass over coal is carbon neutrality. This advantage can be considered through two aspects. Firstly, it is more environmentally-friendly, as it has zero carbon footprints. Secondly, the economics of its exploitation can be enhanced due to carbon taxes. The values of the taxes vary from country to country. In view of this it is reasonable to expect that over the years the use of torrefied biomass for gasification should become more interesting. Furthermore, it is possible, that at some point, it will become more cost-effective than coal. The current prices of coal, and torrefied biomass are 11.0 €/MWh and 26.7 €/MWh, respectively. It is obvious that coal is much cheaper than torrefied biomass but, on the other hand, biomass is a renewable energy-source and has lower sulphur content that reduces the costs of desulphurisation. Furthermore, the lower ash content is another advantage of the torrefied biomass as it reduces the costs of the ash handling process.

A mixture of coal and biomass in a ratio 1:1 was used during our calculations. This ratio was considered for simplicity, and further work would include optimisation of the whole process, including the aforementioned ratio. It is reasonable to expect that the optimal ratio would depend on the price ratio between coal and biomass.

2. Methods

All of the mentioned processes were modelled using the Aspen Plus program package. The Peng–Robinson thermodynamic method was chosen for the gasification, water–gas shift, and methanol production sections, whilst the PC-SAFT (perturbed-chain statistical associating fluid theory) [17] property method was employed for the Rectisol process. Czech coal from Ledvice and torrefied biomass from Ref. [18], having the compositions stated in Table 1, was used for all the simulations.

2.1. Gasification process

The process of gasification has been known for several centuries and until recently only coal had been used as a raw material. Due to the development of the torrefaction process and due to the introduction of carbon taxes, biomass is also being considered as a possible raw material for the high temperature gasification process. Two 500 MW gasifiers were used during our simulations, with a mixture of coal and torrefied biomass as the raw material. The amounts of coal and biomass were calculated in such a way that each of them ensured 250 MW within each gasifier. The calculations were carried out using lower heating values (Table 1),

Table 1
Composition and heating values of coal and torrefied biomass.

Parameters		Testing method	Coal	Torrefied biomass
Moisture	%wt	ASTM D 5142	14.15	35.63
Ash	%wt	ASTM D 5142	10.61	4.47
Volatiles	%wt	ASTM D 5142	40.48	20.69
C-fix	%wt	ASTM D 5142	34.76	39.21
Carbon	%wt	ASTM D 5373	56.36	78.76
Hydrogen	%wt	ASTM D 5373	4.40	4.29
Nitrogen	%wt	ASTM D 5373	0.83	0.05
Oxygen	%wt	Calculated	12.46	16.83
Sulphur	%wt	ASTM D 4239	1.19	0.07
LHV	MJ/kg	DIN 51900	21.73	18.09

resulting in the 38,515 kg/h of coal and 49,833 kg/h of biomass needed within each reactor. The coal must be dried before entering the gasifier. After drying to a moisture content of 1.5%, the pulverised coal is mixed with the pulverised biomass and the mixture conveyed to the gasifier through a lock-hopper system with CO_2 as the conveyance-gas with an assumed loading of 300 kg/m^3. Gasification takes place in the presence of steam as moderator and 95% oxygen from an air separation unit. Gasification was modelled by calculating the equilibrium composition using the minimisation of Gibbs free energy. The pressure within the gasifier was set at 40 bars. The outlet temperature of the gasifier was set at 1450 °C by varying the flow-rate of the oxygen. The heat loss from each gasifier was assumed to be 10 MW and the conversion of carbon was assumed to be 100%. The raw gas was cooled to around 210 °C by direct water quenching and subsequent mechanical cleaning.

2.2. Syngas cleaning and preparation

The syngas obtained from the gasification process has the potential to be used in further chemical synthesis. Before it enters the methanol production process, several cleaning processes must be carried out, together with composition optimisation. Firstly, the whole amount of the sulphur must be removed from the syngas as sulphur is very hazardous for the catalyst used for methanol production and WGS (water gas shift) reaction [19]. Several methods for sulphur removal are commercially available (Rectisol, Selexol etc.). The Rectisol process is normally used, where deep desulphurisation of the synthesis-gas is necessary [20] and this was the reason why it was chosen for our work. Sulphur is mainly present as hydrogen sulphide, which is easily removed below 0.1 ppm using the Rectisol process [21]. Sulphur compounds are absorbed in chilled methanol (−45 °C) within an absorption column. Methanol with the dissolved sulphur compounds is then conveyed to a rectification column, where the sulphur compounds are removed and methanol is recycled back to the refrigeration system and absorber. The captured H_2S is converted into elementary sulphur within a Claus plant. Syngas must be cooled before it is introduced into the Rectisol process. The released heat is used to heat the synthesis gas after desulphurisation and to raise low pressure steam. Part of it is used for the water gas shift reaction, and the remainder is expanded within a steam turbine.

The low pressure steam is added to the sulphur-free syngas and the mixture is conveyed to the water gas shift (WGS) process. The WGS reaction is a very important part of the overall process as it is used to ensure the suitable ratio of CO_2:CO:H_2 needed for the methanol production. The following exothermic reaction takes place during the WGS process:

$$CO + H_2O \rightleftharpoons CO_2 + H_2 \tag{1}$$

The reaction temperature is 375 °C, and pressure 40 bar. As can be seen carbon monoxide is converted to carbon dioxide and hydrogen. Around 60% CO conversion was necessary in our case; therefore the steam-to-CO molar ratio was set at 1.1 [22]. The WGS process is the most frequently used process for ensuring a suitable ratio of CO_2:CO:H_2. However, there are also certain other possibilities such as the addition of hydrogen obtained via water electrolysis. This method is interesting but due to the high price of electricity and the low efficiency of water electrolysis it has not been used commercially.

The carbon dioxide produced during the WGS process must be separated from the syngas in order to ensure a suitable ratio of CO_2:CO:H_2 for the commercially-available catalyst for the methanol production being required to be 5:28:63 [23]. The removal of CO_2 occurs during the second stage of the Rectisol process. The principle of CO_2 removal includes it's absorption in methanol at a low temperature. Methanol with the dissolved CO_2 is then expanded to low pressure and the carbon dioxide is desorbed during the expansion at several stages and can be compressed and stored under the earth or liquefied. During the expansion the methanol cools down; therefore it does not need additional cooling before recycling to the absorber. All the CO_2 could be removed from the syngas by using the mentioned process, but in our case 7% of it remained in the syngas mixture in order to obtain proper syngas composition. The two stage Rectisol process was used during the simulations because very pure CO_2 is produced with no sulphur compounds. Therefore the released CO_2 could be further used for the productions of different chemicals.

2.3. Methanol production

Methanol is a widely-used chemical. It is used as a common solvent in organic synthesis, and also as a raw material for many chemical processes. It can be produced using different technologies and its production from syngas is one of the more frequently used technologies.

As in many chemical syntheses a suitable catalyst must be used in order to achieve desirable conversion and selectivity of the main product. One of the commercially-available catalysts for methanol production is the Cu/ZnO catalyst [23]. In addition to the composition of syngas, pressure and temperature within the reactor are the more important parameters in order to ensure suitable conversion and selectivity. The reaction temperature is set within a range between 240 and 250 °C and the reaction pressure is 51 bar [23,24]. The following two reactions, together with reaction (1), take place within the reactor during the methanol synthesis:

$$CO + 2H_2 \rightleftharpoons CH_3OH \tag{2}$$

$$CO_2 + 3H_2 \rightleftharpoons CH_3OH + H_2O \tag{3}$$

The mechanism for methanol formation has not yet been fully understood but all scientists agree that these three reactions are simultaneous. All three reactions are exothermic and it is absolutely essential to avoid overheating the synthesis catalyst. It is for this reason that the tubes within the reactors are cooled by water, thereby producing saturated steam. The Cu/ZnO catalyst is a very selective catalyst; therefore the amounts of the produced side-products are very low. These side-products include higher alcohols, alkanes, dimethyl ether, etc. All reactions, together with partial conversions of the reactants that were used in the simulation, are listed in Table 2 [23,25].

Methanol synthesis occurs in a series of plug-flow reactors that are simulated in Aspen Plus using an RStoic reactor with the same conversion of reactants. As can be seen from Table 2, the conversion is not that high and that is why large parts of the unreacted reactants are recycled back to the reactor. These products are firstly cooled to 30 °C and the condensed crude methanol is separated

Table 2
Reactions and partial conversions of reactants within the methanol synthesis reactor.

Reaction	Fractional conversion	Of reactant
$CO + 2H_2 \rightleftharpoons CH_3OH$	0.35500	CO
$CO_2 + 3H_2 \rightleftharpoons CH_3OH + H_2O$	0.17800	CO_2
$2CO + 4H_2 \rightleftharpoons CH_3CH_2OH + H_2O$	0.00090	CO
$CO + H_2O \rightleftharpoons CO_2 + H_2$	0.01800	CO
$3CO + 6H_2 \rightleftharpoons CH_3CH_2CH_2OH + 2H_2O$	0.00040	CO
$2CO + 4H_2 \rightleftharpoons CH_3OCH_3 + H_2O$	0.00007	CO
$CO + 3H_2 \rightleftharpoons CH_4 + H_2O$	0.00050	CO

Table 3
Composition of the final product.

Component	Mass fraction
Methanol	0.9998
Ethanol	0.0001
Water	Trace
CO_2	Trace
Total mass flow(kg/h)	58,545

within a flash separator. The gaseous phase consisting mainly of unreacted reactants is split and a certain percentage is purged from the synthesis loop to eliminate the inert material; the remainder is compressed and mixed with fresh synthesis gas and introduced to the synthesis reactor. Crude methanol is transported to the downstream process for further purification.

The downstream process consists of distillation columns for the methanol purification. Methanol is separated from the water, small amounts of ethanol, and the dissolved reactants. The separation can be performed using three or four distillation columns. The first column is used for the separation of the volatile compounds (CO, CO_2, CH_4, and dimethyl ether). Only water and ethanol are left for removal after the first column. Theoretically, this can be done using a single column but usually a combination of two or three columns is used in order to obtain better heat integration. Due to the similar properties of methanol and ethanol, the separation of these two components is a challenging process, and this is also the reason for utilising a combination of several columns.

2.4. *Economic analysis*

The method of NPVs (net present values) is used in order to determine the economic efficiency and validity of the overall process. The NPV is a commonly-used method for the calculation of economic feasibility. This method uses the values of capital and operating costs, prices of products, and the annual discount rate. It in fact calculates the future value of the revenue.

The estimated lifetime of the equipment is 30 years [26]. It is reasonable to expect that the price of raw material and products would vary over that period of time. That is why predicted prices of raw material and products are used for the calculation of the NPV. As mentioned previously, this method, on average, outperforms the random walk price change or the extrapolations of recent price trends.

2.4.1. *Estimation of capital costs*

The value of the capital cost is one of the variables that must be calculated in order to determine NPV. Several parameters and indexes are used for the calculation of capital cost. The main equation used for estimating capital (investment) costs is $C = n^{e}C_0[S/(n\cdot S_0)]^{f}$,where C is the cost of a process unit, n is the number of equally-sized units, C_0 is the cost of a reference unit, S is the capacity of a process unit, S_0 is the capacity of a reference process unit, e is the cost scaling exponent for different numbers of equally-sized units, and f is the cost-scaling factor [27]. As the reference costs are taken from different years, the CEPCI (chemical engineering price cost index) was taken into account for the C_0 calculation [28]. The present reference cost C_0' is calculated using the following equation $C_0' = C_0\cdot i'/i$, where i' is the present value of CEPCI and i is the value of CEPCI at the time when the reference's cost was determined [29]:

The calculation of the capital cost of the overall process is represented in Table 4. The process is divided into several sections, and the total capital cost is calculated as the sum of the costs of individual sections.

The Siemens gasifier island includes the entrained flow gasifier (total quench), the dry feed system, the black water treatment, the slag handling system, and the raw gas treatment [30]. Acid gas removal is in fact a two stage Rectisol process for the selective removal of H_2S and CO_2. Several assumptions are taken into account for the calculation of capital cost. Firstly, it is assumed that torrefied biomass has similar tenacity properties as coal [11], and this is taken into account when calculating the costs for coal handling. The values of the CEPCI indexes are annual values and for the present value of CEPCI the 2012 value is taken into consideration [28].

2.4.2. *Estimation of operating costs*

Operating costs are associated with the energy-consumption, the prices of the reactants and raw materials, the maintenance costs, etc. The operating costs for individual processes are calculated using different methods, depending on the available data.

The operating costs of the coal preparation, Rectisol plant and Claus plant are determined using the reference value of the operating costs [19]. This value is then multiplied by the scaling factor that is equal to the quotient between the reference capacity and the capacity of our process. The values of the operating costs for the mentioned processes are calculated and presented in Table 5.

Furthermore, the operating costs of some processes including ASU (air separation unit) and O_2 compression, the conveyance gas compression, methanol production, and CO_2 capture and storage, are calculated using the amounts of electricity needed for individual processes. The base load electricity price in Slovenia is estimated to be 50 €/MWh. The amount of electricity needed for the mentioned processes is presented in Table 6.

When calculating the operating costs it is assumed that the annual number of working days is 350, resulting in 8400 working hours per year. The only cost of the WGS process is steam needed, and as steam is produced during our process the overall operating costs of the WGS process are negligible [19].

Finally, the last parts of the operating costs are the costs of raw materials. The amounts for carbon taxes are also taken into consideration within this section. As biomass is considered as a

Table 4
Calculation of capital costs.

Process	Scaling parameter	S	S_0	C_0 (M€)	Reference/year	C_0' (M€)	n	f	e	C (M€)
Coal and sorbent handling	Coal (tonne/day)	4003	5447	30.4	[27]/2008	30.9	1	0.67	0.9	25.1
ASU and O_2 compression	O_2 (tonne/day)	3796	2035	80.2	[27]/2008	81.5	2	0.67	0.9	145.2
Gasification island (total water gasifier)	MW based on LHV	1000	500	112.8	[30]/2012	112.8	2	0.67	0.9	210.5
Acid gas removal	CO_2 (tonne/h)	205	2771	806.2	[31]/2011	804.3	1	0.67	0.7	140.5
Claus plant	S (tonne/day)	55	96	5.4	[19]/2007	6.1	1	0.67	0.9	4.2
WGS	MW based on LHV	1000	815	7.0	[27]/2008	7.1	2	0.67	0.9	9.6
Methanol production	MeOH (tonne/day)	2469	5000	61.6	[24]/2005	76.9	1	0.67	0.9	47.9
Methanol distillation	MeOH (tonne/day)	2469	5292	14.4	[23]/2008	16.1	1	0.67	0.9	9.6
Combined cycle power plant	MW	51	69	30.0	[32]/2003	48.7	1	0.67	0.9	39.7
Total capital cost [M€]										632.2

Table 5
Calculation of operating costs based on reference values.

Process	Scaling parameter	Reference capacity	Capacity	Reference cost (M$)	Cost (M$)
Coal processing	MW based on LHV	1699 [27]	1000	9.49	5.59
Rectisol and Claus plant	Sulphur (tonne/day)	96.0 [19]	54.6	8.53	4.85

Table 6
Calculation of operating costs based on electricity consumption.

Process	Electricity needed (MW)
ASU and O_2 compression	69.7
Conveyance-gas compression	2.0
Methanol production	12.5
CO_2 capture and storage	20.0

carbon neutral fuel, the amount of carbon dioxide that would be emitted during biomass oxidation is subtracted from the amount of carbon dioxide emitted during the overall process. As can be seen from Table 7, the amount of carbon present within the biomass is greater than the emitted amount in our process, meaning that surplus in the form of coupons can be sold on the market.

The prices represented in Table 7, are the current prices of the raw materials. Its future prices, together with the predicted prices of products are presented in Figs. 2 and 3.

The price of the torrefied biomass is calculated using the price of wood chips. This price, given in €/MWh, is then divided by 0.9 as biomass loses 10% of its heating value during the torrefaction process [12].

The price indices for the next ten years are published by the World Bank, and they are updated every three months [34]. The price indices of raw materials are used in order to obtain the future prices of biomass. The World Bank also publishes the price forecasts for some commodities (coal, crude oil, etc.), but the price indices of raw materials are used because biomass is excluded from the mentioned commodities. In the case of electricity the energy price indices are used, and in the case of sulphur the minerals and metals price indices are taken into consideration. On the other hand, for obtaining future prices of coal, the price forecast of Australian coal is adjusted to the Slovenian market.

The value of the carbon tax in Slovenia is taken into account for the price of CO_2 emission. This value, together with the projections given by MIT (Massachusetts Institute of Technology), is used for the calculation of future values of carbon taxes [35]. As the values of carbon tax vary from country to country, the carbon tax projections were adjusted to the Slovenian market.

The value of the maintenance costs varies between five and six percent of the capital costs [36]. In our work it was estimated that the maintenance cost would amount to 5.5% of capital costs, resulting in 34.76 M€ per year.

2.5. Data for calculating the net present values

Besides all the costs calculated in the previous chapters, slightly more information is necessary in order to calculate the net present value. Firstly, the future prices of the products should be estimated. The main product of the overall process is methanol, and its price over the past several years is presented in Fig. 1 [37].

Table 7
Prices of raw materials and CO_2 emissions in 2013.

		Price
Net amount of coal (MW based on LHV)	500	11.06 €/MWh
Net amount of torrefied biomass (MW based on LHV)	500	26.66 €/MWh [30]
Net amount of CO_2 (tonne/h)	−60.02	14.40 €/tonne [33]

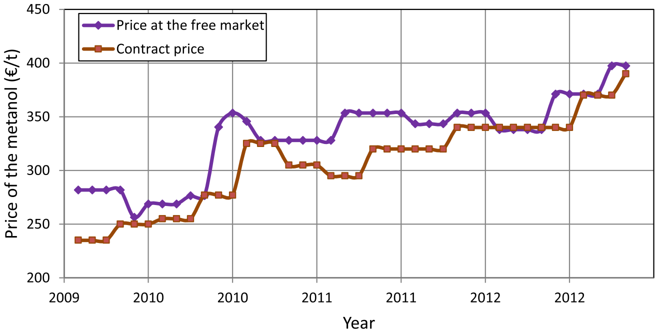

Fig. 1. Price of methanol over recent years.

The current price of methanol is 390 €/tonne. In order to obtain future prices of methanol the price projections given by HIS Inc. are taken into consideration [38]. The predicted prices of sulphur and the values of carbon tax are represented in Fig. 3.

The side-product of the overall process is sulphur. The price of it is within the range between 180$ and 210$/tonne [39]. An average price of 195$/tonne or 152.1 €/tonne is taken as the present cost of sulphur.

The combined cycle power plant produces around 51 MW of electrical energy. For this calculation it is assumed, that it would be sold on the electricity market.

The estimated future prices of coal, biomass, and electricity are represented in Fig. 2. The prices are given in €/MWh. The mentioned price indices and forecast are available until 2025 only, and that is why further prices (until 2043) were obtained using the extrapolation method.

It can be seen from Fig. 2 that the prices of coal and biomass would increase in the future. The increment would be greater in the case of biomass. The probable reason for this fact is the EU policy that promotes biomass usage for heating purposes, since biomass is considered as a renewable energy source, and increase in consumption would also mean an increase in the price. On the other hand the price of electricity would remain approximately constant within the mentioned period of time.

The projected prices of the products, and the estimated values of the carbon tax are represented in Figs. 3 and 4, respectively. The price projections of the sulphur are available until 2025 only; therefore extrapolation is used once again.

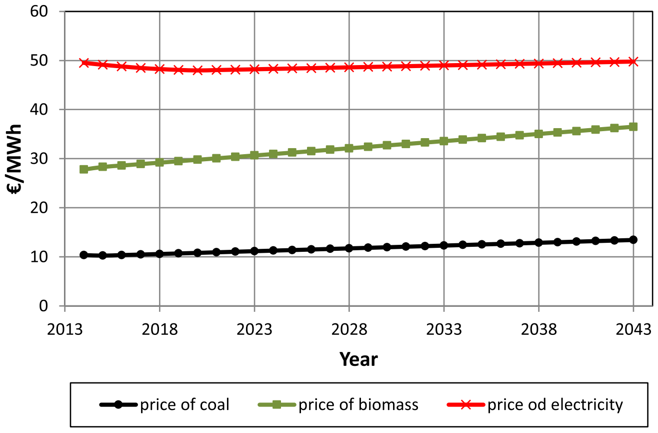

Fig. 2. The estimated future prices of coal, biomass and electricity.

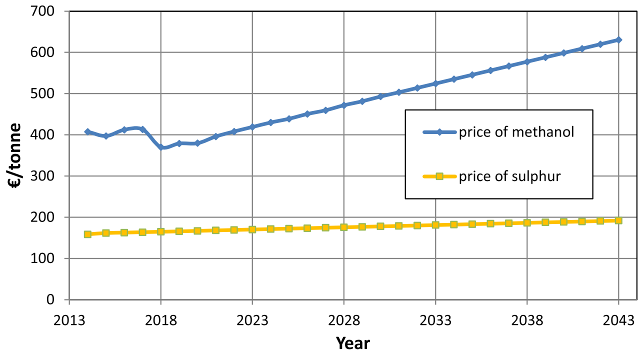

Fig. 3. The estimated prices of methanol, sulphur and the values of carbon tax.

It can be seen that the price of methanol would first decrease but after several years the price would be at the present price level and would continue to increase. That trend would have a positive influence on the net present values. Also the values of carbon tax would increase and that enhances the feasibility of biomass conversion to methanol.

Finally, the last parameter needed for the calculation of NPV is the annual discount rate. The current Slovenian rate is 1.75% [40]. The value of this rate is extremely low and this is because of the present economic crisis. This project is a long-term investment and that is why it is reasonable to expect that the annual discount rates might change in line with economic recovery. It is because of this that the value of the annual discount rate (4%) before the global economic crisis is taken into consideration [41]. The calculation would be even more accurate, if the predicted values of annual discount rate were used, but such predictions are very unfavourable.

Annual profit is calculated by the following equation $A_p = P_m + P_s + P_e - O_t - M_t$, where, P_m is the price of the total amount of methanol produced, P_s is the price of the total amount of sulphur produced, P_e is the price of the total amount of electricity produced, and M_t is the maintenance cost.

3. Results and discussion

3.1. Product composition and cold gas efficiency of the process

The composition of the final product is presented in Table 3. It can be seen that the obtained methanol is very pure and meets the AA grade methanol specifications [42]. Such methanol can be used as a solvent or starting material in many chemical processes such as acetone production, gasoline production, etc.

The overall process consumes a lot of electrical energy for a variety of process units. The electricity is also produced using a combined cycle. The purge-stream and the volatile compounds from the first column are burned within the gas turbine. Part of the flue gas from the gas turbine is used for coal drying; the remainder is used for creating steam, which is expanded within the triple-stage steam turbine. The heat released during the water–gas shift process is also used for the production of steam, most of the saturated steam produced within the synthesis reactor is used for the distillation columns; the remainder is superheated and expanded within the turbines.

CGE (cold gas efficiency) for methanol was calculated by the following equation: CGE = HHV(MeOH)/HHV(coal), where HHV means higher heating value. The CGE value amounted to 59.9% and 57.7% for the co-gasification case and base case, respectively. The result for the base case is in good accordance with the published literature [43]. In the case of partially using torrefied biomass the CGE is higher compared to the base case. The more probable reason for this is in the composition of the torrefied biomass, it namely contains less ash and more carbon than coal. However, if the torrefaction step with an efficiency of 90% is taken into account, the CGE value drops to 56.8% for the co-gasification case.

3.2. CO_2 emissions

The net emissions of CO_2 per kg of methanol were also calculated using the results of the presented simulation. In the process where only coal is used, 2.45 kg of CO_2 is emitted per each kg of methanol produced, whereas in the process where both coal and biomass are used, CO_2 is not emitted but consumed (due to carbon neutrality of biomass), and for each kg of methanol produced, 0.59 kg of CO_2 is consumed. That is the main reason why combined usage of coal and biomass is ecologically very favourable.

3.3. Net present value

The net present values of the overall process for the basic coal to methanol plant were also calculated in order to check the feasibility of using the mixture of biomass and coal during the gasification process for the further production of methanol. The comparison of the net present values for a period of 30 years is presented in Fig. 5. The green (in the web version) line presents the case where equal amounts of coal and biomass are used (co-gasification case), whilst the black line presents the case where only coal is used (base case).

The capital and other costs for the base case were calculated using the previously explained methods. The capital costs are slightly lower in this case due to the smaller process units needed. On the other hand, the amount of methanol produced is lower in this case as coal has higher ash content than biomass, resulting in a smaller amount of CO being produced during the gasification process. The annual profit is calculated in the same way as in the co-gasification process.

It can be seen that the break-even point in the base case that uses only coal as raw material is approximately five and a half years,

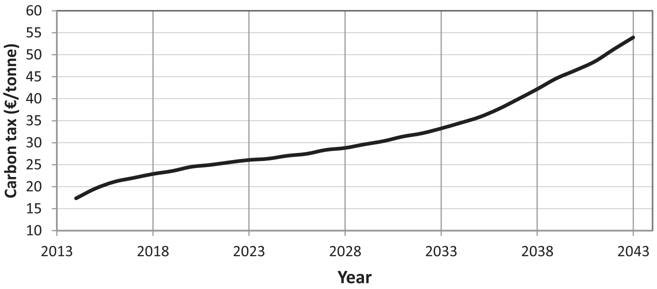

Fig. 4. Estimated value of carbon tax by 2050.

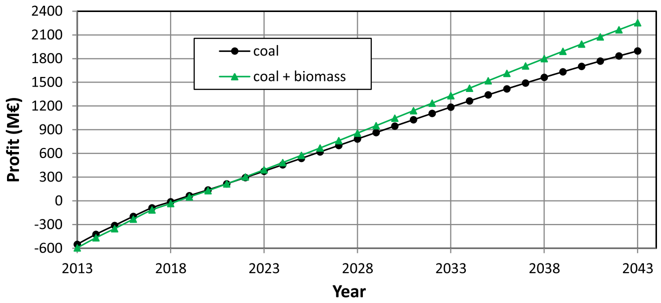

Fig. 5. Net present values for both processes.

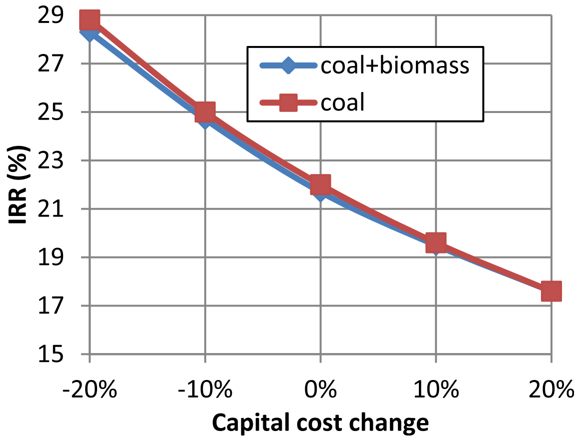

Fig. 6. Capital cost vs IRR.

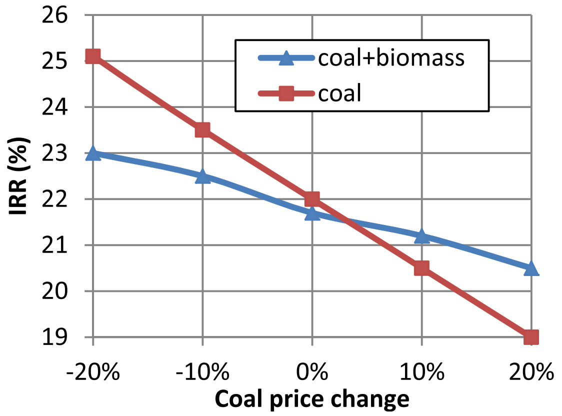

Fig. 8. Coal price vs IRR.

which is a half year less than in the case where a mixture of coal and biomass is used. This means that the base coal to methanol process is economically more efficient at the beginning. However, the net present value of the process that partially uses biomass becomes greater after approximately 10 years. The reason for this tendency can be found in Fig. 4 that presents the estimated future values of carbon tax.

The result would be even better if there were not a decrease in the methanol price over the first few years. The net present value after a period of 30 years would be about 2.23 billion Euros, which would be more than three times greater than the value of the capital cost.

It is easily observed that the differences in the net present values of both processes over 30 years would become greater with higher values of the carbon tax during the 30 year period. The main reason for this is the carbon neutrality of the biomass.

In addition to the break-even point, some other important data can also be estimated using the NPV function. One of such parameters would be the IRR (internal rate of return) [36]. It is in fact the value of the annual discount rate at which the NPV would be equal to zero. The calculated value of the IRR values is 21.4% and 20.7% for the co-gasification case and base case respectively.

3.4. Sensitivity analyses

The sensitivity analyses were performed in order to determine the influences of different independent variables (such as capital costs, prices of products, reactants, and carbon tax) on the net present values. The value of capital cost was varied ±20% and ±10%. The variation influence was measured using the calculation of internal rate of return (IRR). Furthermore, the prices of methanol, coal, biomass, and the carbon tax price are varied in the same manner. The results of the sensitivity analyses are represented in Figs. 6–10.

It can be seen that any changes in methanol price would have the greatest influence on the IRR value. Such change is the most probable as methanol price is strongly influenced by economic business cycles. Furthermore, it is obvious that the coal price change strongly influenced the process where only coal is used, and that is because of the greater amount of coal used in the mentioned process. As can be seen from Fig. 10 the increase in the predicted carbon tax price would have a positive impact on the IRR value for biomass co-gasification, whereas a decrease of over 8% would mean that the base case would be a better option.

4. Conclusion

Slovenia is one of those countries with higher biomass potential due to the high percentage of land covered by forests. The development of torrefaction technology enables wider usage of biomass and this fact could help Slovenia develop its biomass potential. Torrefied biomass has similar properties as coal and that is the reason why it could be used within entrained flow coal gasifiers.

The process of coal gasification is already present on a large scale, meaning that its cost effectiveness is proven. Even though

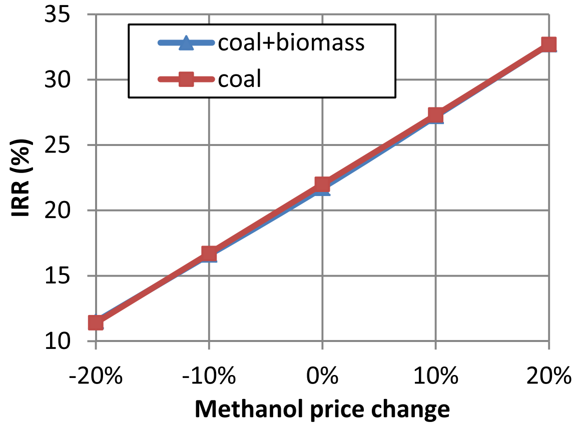

Fig. 7. Methanol price vs IRR.

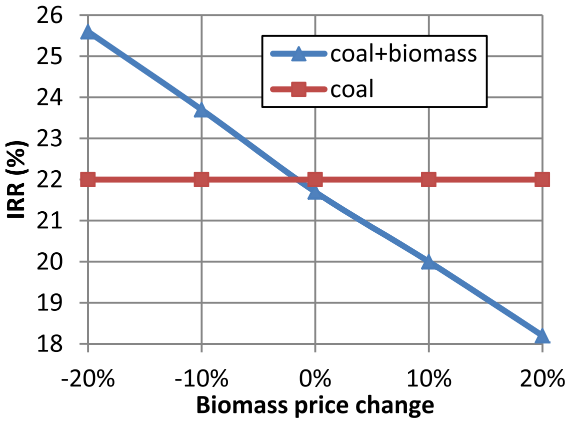

Fig. 9. Biomass price vs IRR.

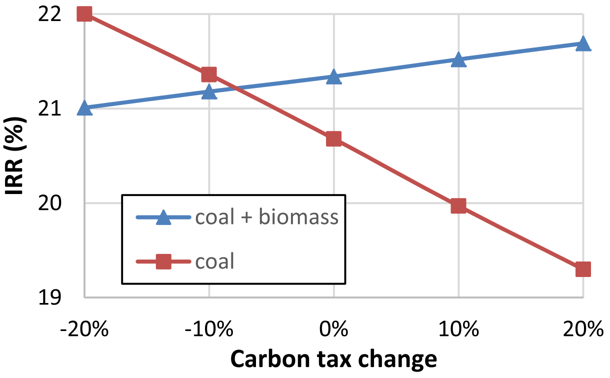

Fig. 10. Carbon tax price vs IRR.

biomass has a higher price, this paper provides evidence that mixed biomass and coal gasification is also a promising technology. It is reasonable to expect that the mentioned process would become even more interesting due to the carbon neutrality of the used biomass.

The gasification process is followed by the methanol production. The product of gasification process is raw syngas, and the production of methanol is only one of the possibilities for syngas usage. Our future work would include the evaluations of other possibilities for its usage in addition to methanol production. However, in this paper it is taken that the entry ratio of coal and biomass is 1:1, and this could be optimised in future work.

Finally, the main goal of this paper was to show that the usage of torrefied biomass during the gasification process is economically feasible and ecologically friendlier. The presented economic analysis proved that usage of a mixture of biomass and coal within entrained flow gasifiers is feasible, and would become economically even better than using coal only. Furthermore, during the 30 year period the net emissions of CO_2 would be lowered by 40.8 million tons. It can be, however, concluded that the main contributor for the economic feasibility of the co-gasification of biomass is carbon tax that should be maintained high enough in order to make biomass economically favourable over fossil sources.

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